RESEARCH REPORT
(for RTOPs and Grants)

1. Title EPISODE – Software for Trajectory Generation and Nonlinear Control		**2. Date Prepared** 08 22 2008
3. Performing Organization: Jet Propulsion Laboratory		**4. RTOP/Grant No.**
4.A. JPL Project Number: **102294 982745.03.03**	**(Per GSK Policy, this serves as the Work Authorization Document)**	**4.C. NASA WBS NUMBER** **982745.02.02.03.03**
5. Investigator Telephone Jeff Jewell 818-354-6211	**6. NASA Program Manager** **Joseph Bredekamp**	**7. NASA Division** SMD
8. Reference **NRA Number: NNH07ZDA001N-AISR Other:**		

9. Funding Profile:	**FY'07 Prior Approvals**	**FY'08 Current Guideline**	**FY'08 Current Request**	**FY'08 Current Overguide**	**FY'09 Next Request**
	$ 248,970 K	$ 249,995 K	$ 249,995 K	$ K	$ 248,488 K

10. Description

Project objective is to develop advanced trajectory generation methods utilizing two recent advances – the discovery of the "inter-planetary superhighway" (exact solutions of 3 body dynamics which asymptotically wind on and off periodic orbits, and can be used for transport to widely separated regions of configuration space), and low-thrust (electric ion) propulsion which enables larger cumulative delta V relative to chemical rocket propulsion, but presents a challenging trajectory design problem due to potential orbit instability and lack of control authority. Both technologies have been flight tested – the IPS concept was used to design the trajectory for the Genesis mission (computing this trajectory as a solution to an optimal open loop problem would have been very challenging without insights from nonlinear dynamics), and Deep Space 1 used ion propulsion. The need for advanced trajectory generation methods arise in the early phase of mission design, where a broad range of low-fidelity mission scenarios and associated trajectories can be surveyed, with refined, increasingly accurate trajectories developed once decisions balancing science return and mission risk have been made.

Our approach to the early phase of mission design is to use a probabilistic exploration of solutions to the trajectory design problem (a constrained optimization problem where typically fuel cost is minimized with constraints on maximum allowed time of the mission, the solution of which can be shown to satisfy a two-point boundary value problem for a system of differential-algebraic equations, which are notoriously difficult to solve numerically). We have developed methods to quickly generate promising trajectories using insight from dynamical systems theory (the "IPS") and assign a probability to these initial guess trajectories based on their residual error (the trajectories are substituted into the differential algebraic equations associated with the design problem to compute the error along the trajectory). We have been able to prove that as the "entropy" of the probability of trajectory solutions is reduced (the volume of trajectories decreases), we will be concentrated on sets of trajectories arbitrarily close to the optimal control solutions. This then justifies the approach computationally – we can continue to probabilistically refine our entire ensemble of trajectories allowing a broader collection of trajectories to be computed (with some target degree of accuracy for fixed computational expense) before selecting a subset for follow-on high fidelity design.

Accomplishments for FY08: While the initial version of the code was developed and tested in FY07, we have spent our efforts in FY08 refining the generation of trajectories guided by insight from dynamical systems theory, as well as refine the code to implement a Markov Chain Monte Carlo probabilistic search through the space of trajectories. With regard to the former, we have developed a method of generating interesting "waypoints" which addresses the challenge of trajectory design in the full 3 and 4 body problems. Previous trajectories, such as for Genesis, were designed using Poincare sections to find intersections of the invariant manifolds of the underlying 3 body dynamics (restricted to a plane), thereby locating potential waypoints near a trajectory solving the science goals. It is non-trivial to extend this technique to higher dimensional problems. We have implemented instead an approach where initial and final endpoints of the trajectory are integrated forward and backward in time – these two segments will not meet of course, and so we patch together these two segments by solving a linearized variational problem. We have written the code so that the user can input any dynamical system of interest (although we are applying this to the 3 body problem), with the smoothing of the two segments integrated forward and backward from the endpoints computed using the Jacobian of the dynamics along these segments (which is computed automatically from the user supplied routine for the dynamics – we are using the software ADOLC, but ADIFOR would be another option). Once the smoothing continuous path has been computed, we are able to build a Gaussian probability density for waypoints at the midpoint of the smoothed path (the "width" and shape of the Gaussian are determined form the Jacobian of the dynamics along the smoothed path). This provides a measure of uncertainty in waypoints along a true optimal control solution in a way directly determined by the error in the smoothed trial trajectory. This process can be hierarchically and recursively continued to generate a lattice of waypoints. Once this initial phase is complete, we can then use MCMC to survey many trajectory classes which pass through or near these waypoints.

Goals for FY09 will be to demonstrate the automated search with waypoint generation and MCMC for low-fidelity trajectory generation for the full 3 body problem. Our main goal is to use the now developed code to quantify the rate at which accuracy of the ensemble of trajectories increases (i.e. on average) with computational expense, in order to determine the optimal point at which to call high-fidelity deterministic optimization routines. In this manner, we will have a method which provably converges to globally optimal solutions, and provides well-refined initial guess solutions to more traditional deterministic optimization routines (which suffer from convergence to local minima if not started from an extremely good initial guess). We anticipate 1 or 2 papers will be written summarizing the method and numerical results obtained.

Approval:	**Date:**	**Concurrence:**	**Date:**

RTOP PREPARATION INSTRUCTIONS

1. **TITLE: ENTER THE OFFICIAL TITLE. IF THIS IS A NEW EFFORT, ENTER A BRIEF, DESCRIPTIVE TITLE LIMITED TO 73 CHARACTERS. STANDARD ABBREVIATIONS MAY BE USED TO STAY WITHIN THIS TOTAL.**

2. **DATE PREPARED: 01 SEPTEMBER 2005**

3. **PERFORMING ORGANIZATION: JET PROPULSION LABORATORY**

4. **RTOP/GRANT NO. ENTER THE 9 DIGIT RTOP NUMBER. IF THIS IS AN OVERGUIDELINE REQUEST, USE –XX FOR THE 8TH AND 9TH DIGITS.**

4A. **JPL PROJECT NUMBER: THE FIRST 6 DIGITS OF YOUR JPL CHARGE ACCOUNT NUMBER.**

5. **INVESTIGATOR: PI NAME**

6. **NASA PROGRAM MANAGER: SELF EXPLANATORY**

7. **NASA DIVISION: Earth Sun Systems Space Science Universe**

8. REFERENCES: NRA NUMBER IS NOW REQUIRED. THIS NUMBER MAY BE OBTAINED FROM YOUR DPM.

9. SUMMARY OF FUNDING PROFILE:

   a. PRIOR FY APPROVALS: ENTER NOA APPROVALS FOR FY'05.
   b. CURRENT FY GUIDELINE: ENTER GUIDELINE AMOUNT AS IT APPEARS ON YOUR PROPOSAL SELECTION LETTER FOR FY'06. IF NO GUIDELINE OR TBD IS GIVEN, ENTER A ZERO.
   c. CURRENT FY REQUEST: ENTER TOTAL AMOUNT REQUESTED.
   d. CURRENT FY OVERGUIDE: ENTER THE AMOUNT REQUESTED THAT IS OVERGUIDELINE. IF NO OVERGUIDELINE IS REQUESTED, ENTER A ZERO.
   e. NEXT FY BUDGET: ENTER REQUESTED AMOUNT FOR FY'07.

10. DESCRIPTION: IDENTIFY LAST YEAR'S (FY'05) ACCOMPLISHMENTS AND PLANS FOR THE COMING YEAR (FY'06). REFERNCE ANY REFEREED PUBLICATIONS.

11. APPROVAL: LINE ORGANIZATION (SECTION OR DIVISION)

12. CONCURRENCE:

CONCURRENCE	DPM
AISRP	CHUCK NORTON
ASTROPHYSICS	JIM LING
ALL MARS (OTHER THAN MIDP)	BRUCE BANERDT
CLIMATE VARIABILITY	VICTOR ZLOTNICKI
NEO	JAY GOGUEN
PLANETARY ASTRONOMY	JAY GOGUEN
PLANETARY ATMOSPHERES	JAY GOGUEN
PLANETARY GEOLOGY AND GEOPHYSICS	BRUCE BANERDT
SOLID EARTH NATURAL HAZARDS	RON BLOM
SUN EARTH CONNECTION/ LIVING WITH A STAR	JIM LING